

THE DEVELOPMENT AND USE OF A
SPEED VS. DISTANCE GRAPH TIME CALCULATOR
IN THE INTERPRETATION OF LOCOMOTIVE PERFORMANCE

A Thesis

Submitted in Partial Fulfillment of the
Requirements for the Degree of

MECHANICAL ENGINEER

By

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I Development

A. Need

Of prime interest to railroad men is the matter of train schedules and speeds, which is often reflected directly by public opinion and therefore earning ability. With the advent of successful competition train schedules were shortened and consequently train speeds were increased. As a result, more attention is being given to schedules and to keeping trains on schedule under all operating conditions.

As a means of studying actual train operation without having to ride each train, locomotive speed recorder tapes were made available. These tapes are essentially speed vs. distance graphs plotting speed in miles per hour against miles traveled. It is therefore possible to determine the actual speed of any train so equipped at any location, and the tape represents an autograph of a train's performance.

Since these tapes record the speed directly in miles per hour, and as this speed is fluctuating a greater part of the time, any approximation of the time involved is bound to be crude. Because time is actually the value desired, and the speed only that required to make a specific schedule, the problem of converting these tapes into time presented itself.

It is true that complete studies are possible which will forecast a schedule for a particular run with equipment of known characteristics; but here was presented almost the reverse - performance charted complete except for the time value.

B. Description of the Locomotive Speed Recorder.

Although steam locomotives are over 100 years old, generally speaking automobiles have carried speedometers longer than have locomotives. The locomotive ran upon its own right of way and because enginemen carried certified accurate time pieces and because railroad operation and safety depended upon these timepieces, the speed at which the locomotive was operated was determined by the watch and the "mile posts" along the right of way, "Time per mile" it is called, and it is still used to check speed by many railroadmen, including enginemen.

However, speedometers appeared on locomotives and where they have been used for a sufficient time, the enginemen have come to rely on them for their speed indication, rather than "time per mile".

One of the modern types of speed recorders is mechanically operated by a $11\frac{1}{4}$ " diameter "friction wheel" held in contact with the tread of the tire of the right back locomotive driving wheel. This friction wheel drives a centrifugal type governor, spring loaded, through a $\frac{1}{2}$ " flexible drive

shaft made of one inch links, enclosed in a lubricated conduit. At a locomotive speed of 60 miles per hour, this flexible shaft turns 400 R.P.M. and indicates 60 MPH on a suitable dial facing the engineman. This same mechanism moves a $2\frac{1}{2}$ " wide paper tape at the rate of one inch per two miles, while a pencil which is interlocked with the speed hand on the dial plots the speed on this moving tape.

Tape is supplied in rolls up to 2400 miles in length and the used portion is usually removed at each locomotive terminal and forwarded to a central point for examination, study and filing.

A friction wheel drive for the speedometer is used instead of an axle drive for two reasons:-

1. Size or wear of the locomotive driving wheel tire does not affect the accuracy of the speed indication.

2. Attachment of the device to a driving axle is complicated by the fact that crank pins and rods are present and although the device may be located on any wheel which is in contact with the rail, a driving wheel is chosen so that any slipping of the locomotive drivers may be noted by the enginemen and recorded on the tape.

The device is so geared that it will indicate and record back up movements as well as forward movements. This type of speedometer is made in four speed ranges:-

60 MPH Instrument	0-60	MPH
90 MPH Instrument	10-90	MPH
100 MPH Instrument	10-100	MPH
120 MPH Instrument	10-120	MPH

This study is based on the 90 MPH Instrument but it is equally applicable to the 100 and 120 MPH Instruments. Difficulties are to be met when the speed is below 10 MPH due to inaccuracy of the speedometer itself in this speed range, short length of time and distance operated at less than 10 MPH and the detail and dimensions of the calculator developed.

The 90, 100 and 120 MPH Instruments are similar and may be considered the same for the purpose of this paper. The only change necessary is in the cam, which will be taken up later.

C. Statement of Principles.

Since such a graph as is produced on this tape is known as a speed vs. distance graph, there are certain known mathematical values, thus:-

The area under the curve, FIGURE 1, Page 5, is measured as a product of speed (MPH) and distance (Miles) which equals miles squared per hour, a meaningless unit. (See Note. 1.)

If, however, this graph is replotted using the reciprocal of the speed vs. distance to the same scale in miles:-

The area under the curve, FIGURE 2, Page 5, is measured as a product of reciprocal speed (hours per mile) and distance (miles) which equals hours, a simple unit of time. (See Note 2.)

Note 1. Technical Mechanics, Maurer & Roark, Page 140.
Note 2. Technical Mechanics, Maurer & Roark, Page 141.

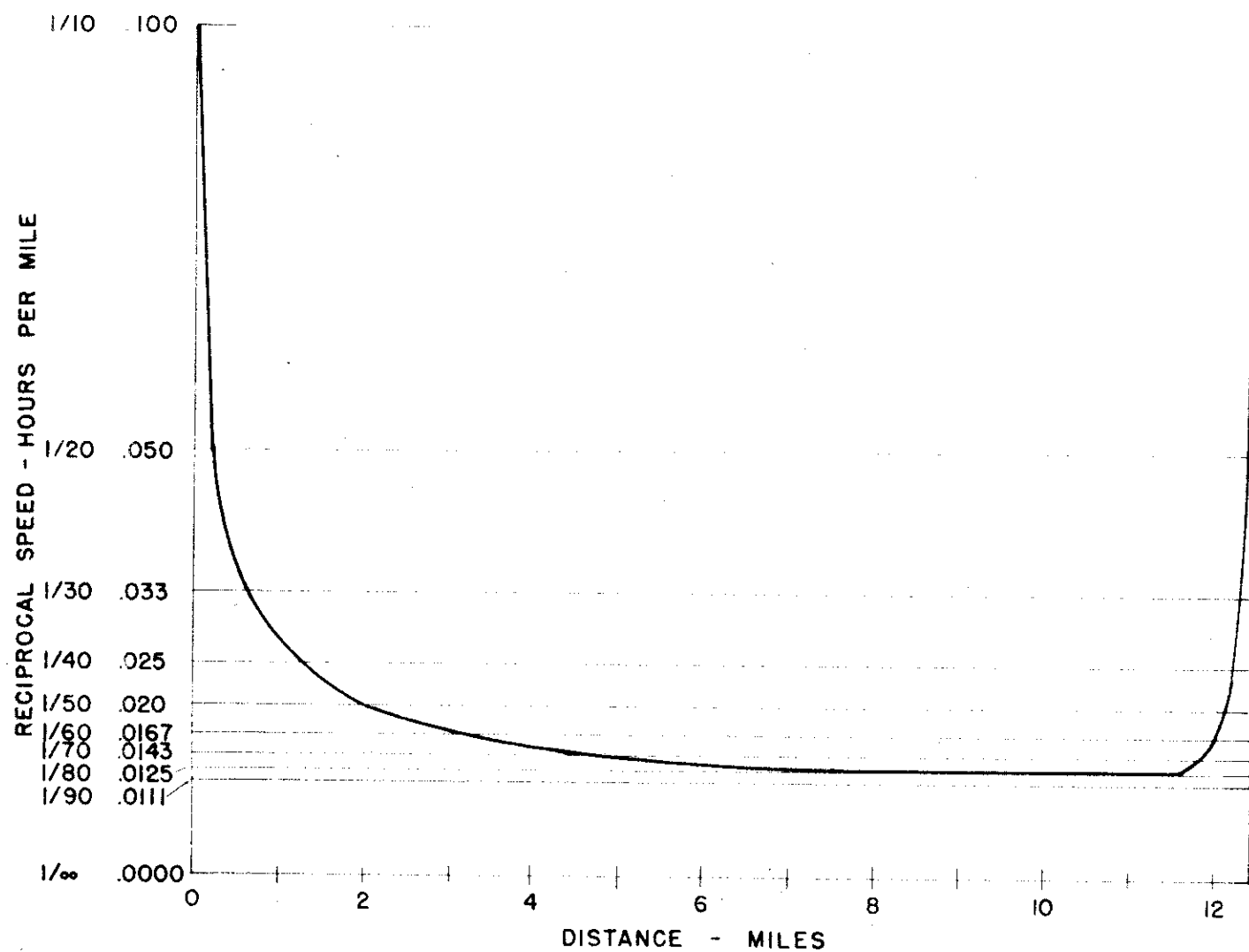


FIG. 2

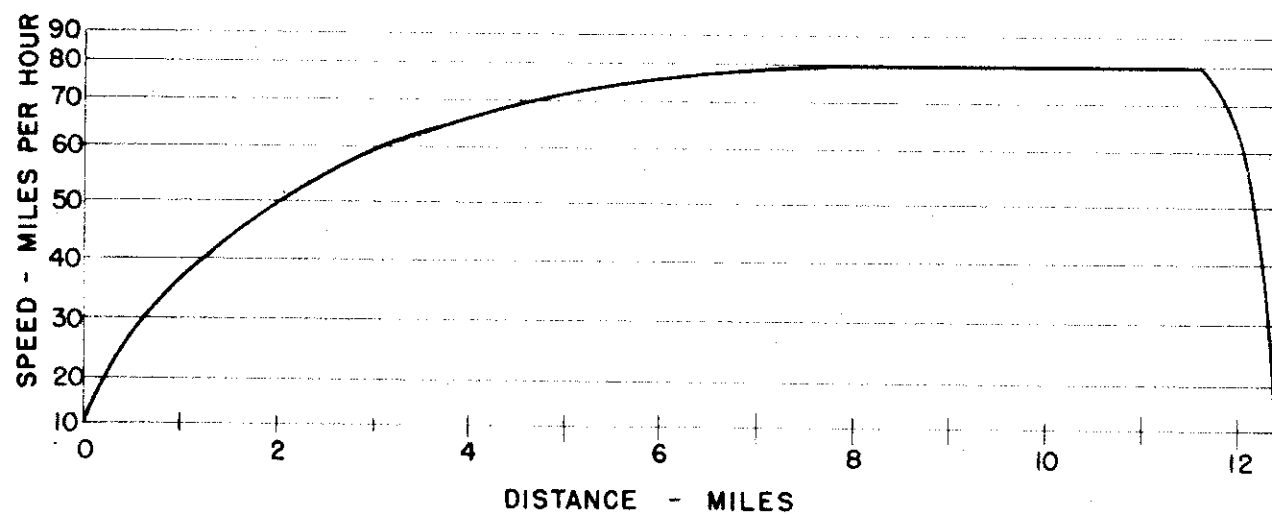


FIG. 1

TYPICAL SPEED VS. DISTANCE GRAPH
AND
CORRESPONDING RECIPROCAL-SPEED VS. DISTANCE GRAPH
LOCOMOTIVE SPEED RECORDER

It is therefore obvious that using a proper planimeter and reciprocal ruled chart paper upon which the tape chart could be replotted, the elapsed time could be determined between any two points on the tape.

Any replotting of curves, however, involves considerable labor, and is subject to error, and if the tape information is to be readily available it should be obtained from a wide basis of actual tapes. Therefore, a short and relatively simple procedure is necessary if maximum use is to be made of the speed recorder tapes.

D. Solution.

It was therefore decided to construct a machine which would plot a reciprocal speed vs. distance graph from a speed vs. distance graph; so that the reciprocal speed curve would be a continuous line instead of a series of points.

A study of the actual speed vs. distance graphs, and the reciprocal ruled chart paper brought up several conditions which it was necessary to satisfy before the machine could be built.

1. The vertical dimensions of the 10-90 MPH tape were not equally spaced.

2. The vertical dimensions on the reciprocal ruled chart paper varied greatly.

3. A cam cut to suit these requirements had to permit a 33:1 ratio of movement between 10-20 MPH speed, for

instance, and a 1:1 ratio of movement between 70-90 MPH speed.

4. The 90 MPH tape measured two inches between 10 and 90 MPH, while the reciprocal ruled chart paper measured 13.86" between 10 and 90 MPH.

Many cams were tried but the great difference in ratio of movement made them self-locking at certain speeds. Finally one method was found where the cam follower was attached to a crosshead sliding in straight line guides and the cam rotated about one end which was pivoted. Through suitable linkage the motion was transmitted so that when the machine was operated by the handwheels in such a way that the follower was kept on the speed vs. distance graph chart line, the pencil plotted on a sheet of paper the exact corresponding reciprocal-speed vs. distance graph.

The area under this graph could then be determined with a planimeter and by using a suitable constant, the elapsed time could be obtained in minutes.

The first cam was cut to handle the 90 MPH speed recorder tapes, and later a second cam was cut for the 120 MPH tapes. It would be possible to cut a cam to handle any speed recorder tape under $2\frac{1}{2}$ " in width with the present machine, and with a slight change in construction, as much wider as is practical to use in this type of recording instrument.

This method, although it did away with replotting the curve by hand, still made it necessary to make two runs; first over the actual speed vs. distance graph, and second, planimentering the area under the newly drawn curve. The tracer arm of the planimeter was then attached to the plotting arm, and instead of replotting the curve, the planimeter followed the reciprocal speed curve accurately, and with proper manipulation, the area under the reciprocal curve was measured simply by following the original speed vs. distance graph. The area under the reciprocal speed vs. distance graph is obtained in square inches, which represents time in minutes, using the proper constant.

This constant depends upon:-

- 1- Units chosen for the abscissa and ordinate of the reciprocal speed vs. distance graph.
2. Constant of the planimeter.
3. Minutes per hour equals 60.

The unit chosen for the abscissa is the mile which measures 0.5 inches and coincides with the distance scale of the speed vs. distance graph.

The unit chosen for the ordinate depends upon the dimension of the reciprocal ruled chart paper, in this instance, 14 inches, which makes one unit equal 140 inches.

The constant of the planimeter in this case is 0.03; that is, the reading of the planimeter is multiplied by 0.03 to get square inches.

The constant of the machine is therefore:-

$$c = \frac{0.03 \times 60}{140 \times 0.5} = 0.0257$$

That is, the time in minutes between any two points equals the planimeter reading $\times 0.0257$, when 14" reciprocal ruled chart paper is used.

If a 7" reciprocal ruled chart paper is used, this constant becomes:-

$$c = \frac{0.03 \times 60}{70 \times 0.5} = 0.0514$$

If a 5" reciprocal ruled chart paper is used, this constant becomes:-

$$c = \frac{0.03 \times 60}{50 \times 0.5} = 0.072$$

The planimeter used is a rule planimeter capable of measuring an area within a rectangle, the maximum dimensions of which are 16" \times 60". A polar planimeter could be used to measure the area under the reciprocal speed vs. distance graph, but the distance measured for each setup of the planimeter would necessarily be limited by the length of the measuring arm. Since the rule planimeter allows measurements to be made up to 60" in length, (equivalent to 120 miles on the speed vs. distance graph), it was decided to make use of this instrument. The measuring roller of this particular planimeter rolls on a special surface on a steel track so that the constancy of surface is not interfered with.

E. Description of Machine Pictures, FIGURE 9 & 10, Pgs.11,12.

The machine chassis is made of steel, moving along a 72" track on ball bearing sheave wheels controlled through a "distance" hand wheel geared to a stationary rack. The "speed" wheel turns a screw which moves a crosshead in guides through a 14" stroke, corresponding to the ordinate distance dimension of the reciprocal ruled chart paper. To this crosshead is attached (1) planimeter carrier arm, (2) reciprocal speed vs. distance charting pencil, and (3) cam follower, a small precision ground ball bearing which is held in contact with the cam through a spring arrangement. This cam follower, integral with the crosshead, moves in a straight line and the cam swings on a cam holder which is pivoted at one end. The cam holder is connected through two levers and a bell crank to a pointer which is used to follow the speed vs. distance graph.

The "speed" wheel makes 80 revolutions to give the crosshead the 14" stroke, and the "distance" wheel in making one revolution causes the machine to travel about $4\frac{1}{2}$ " or 9 miles to the scale of the tapes used.

The planimeter "rule" is placed on the table top about the center of the 14" stroke of the crosshead, and the planimeter carrier arm (1) is carried just enough higher to clear this rule. Normally, pencils are not inserted in (2), the charting pencil holder, as this step is skipped by the

SPEED VS. DISTANCE GRAPH TIME CALCULATOR

SIDE VIEW

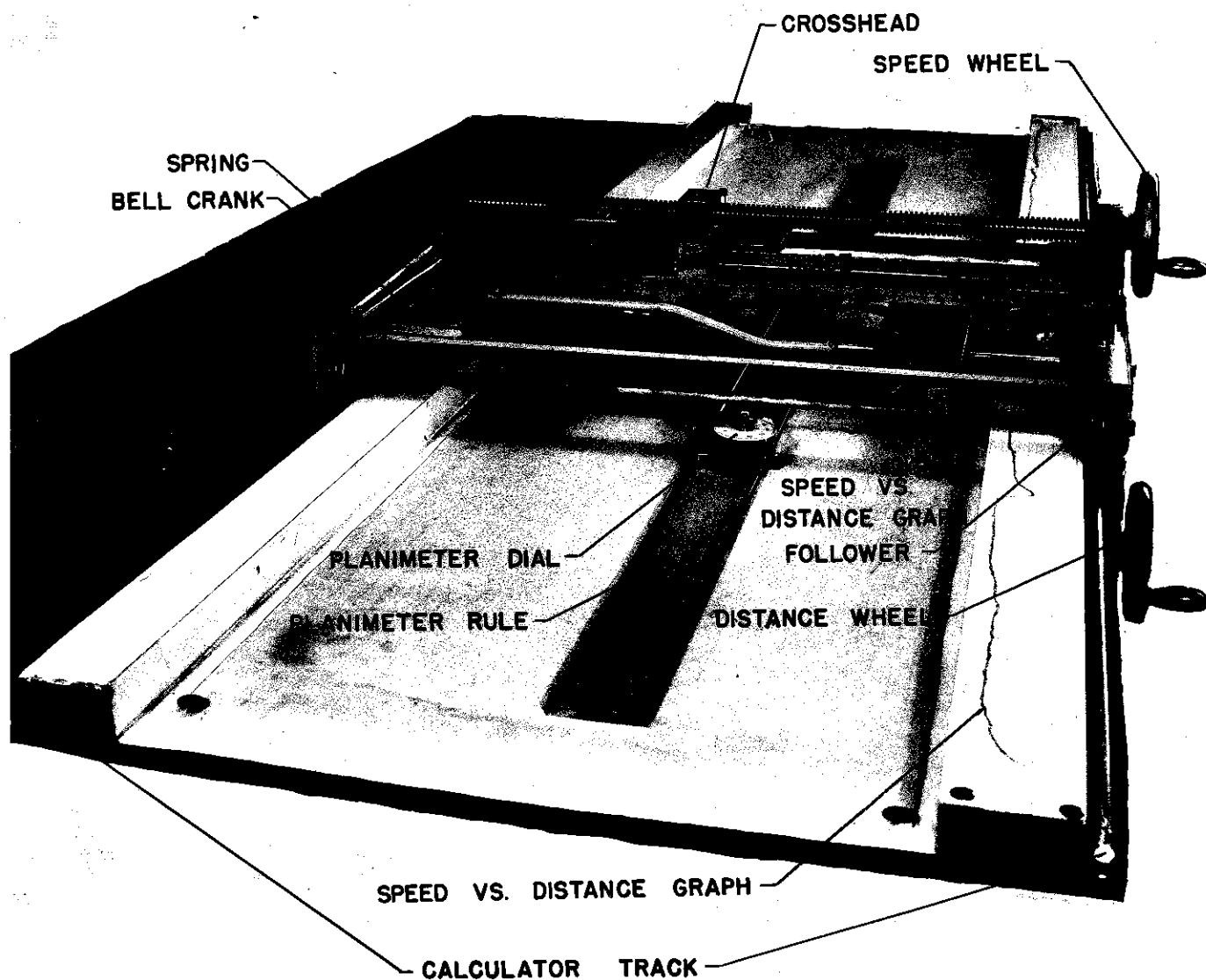
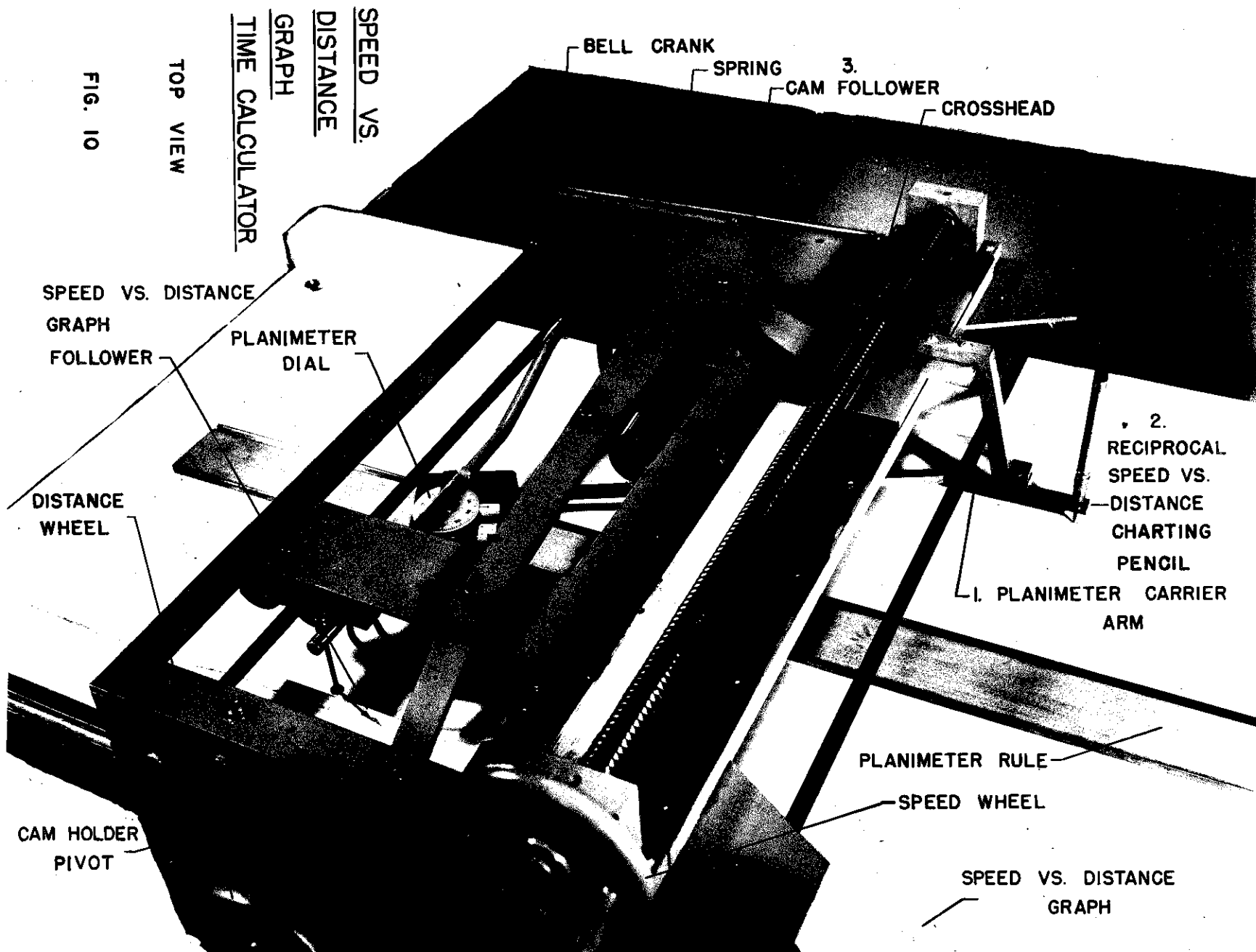


FIG. 9.



use of the planimeter on the reciprocal curve as it is being generated. The accuracy of the machine has been found to be within 1%, which is within the accuracy of the locomotive speed recorders.

II. Uses.

1. Finding time between any two points on a tape,
FIGURE 3, Page 14.

The tape in question has the two points "A" and "B" accurately located and is placed on the machine. The tape follower is placed on the starting point "A" and a planimeter reading is made. The two hand cranks (the speed wheel and the distance wheel) are manipulated so that the pointer follows the actual speed line to the end point "B". At this location, the distance wheel is held fast and the speed wheel is turned until the carriage arrives at the zero position "C". The speed wheel is then held fast while the distance wheel is turned until the pointer reaches point "D" vertically in line with starting point "A", where the distance wheel is stopped and the speed wheel is turned until the pointer is at the starting point "A". The planimeter is read, and the difference between this reading and the original reading is multiplied by the constant, thus:-

$$335 \times 0.0257 = 8.6 \text{ minutes from "A" to "B"}$$

This procedure is then repeated to obtain a check of the planimeter reading. It will be seen that while the actual follower on the tape traverses the area A-B-C-D-A,

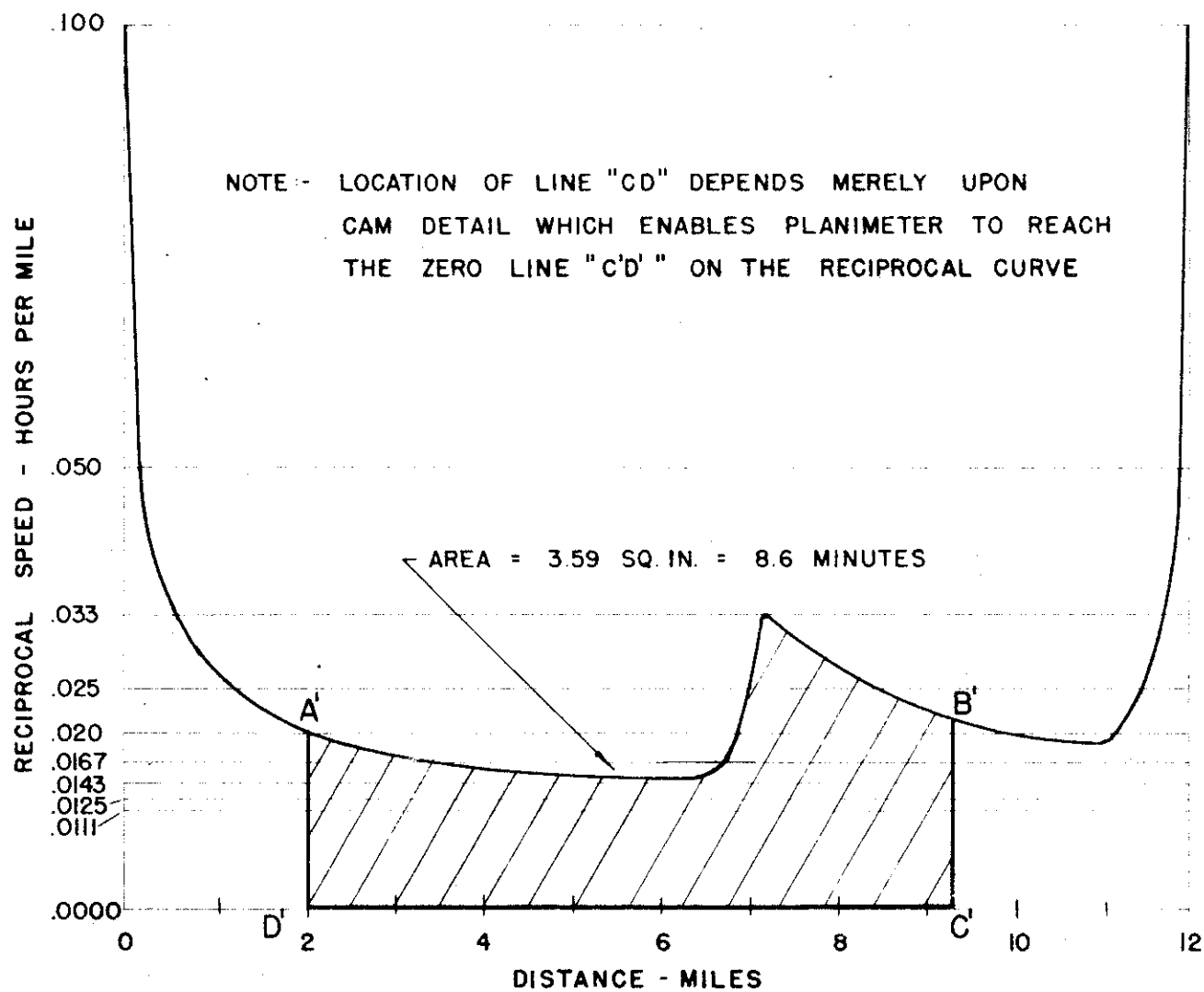


FIG. 4

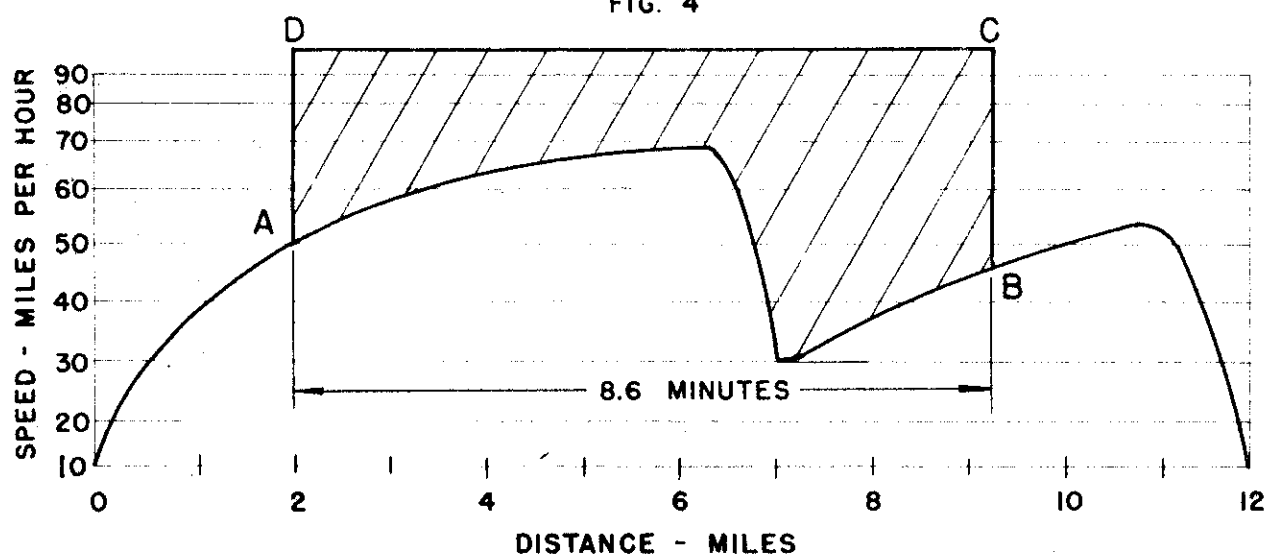


FIG. 3

EXAMPLE OF FINDING TIME BETWEEN ANY TWO POINTS
"A" AND "B" ON A SPEED VS. DISTANCE GRAPH

FIGURE 3, the planimeter actually traveled the path, A'-B'-C'-D'-A', and the time is proportional to the area A'B'C'D'.

2. Loss of time due to a slowdown, FIGURE 5, Page 16.

Point "A" represents any location at which a reduction in speed is necessary and point "C" represents the location where the original speed is regained. Between the two points "A" and "C" therefore, there are two lines, one the actual speed line, ABC, and the other the speed line as would appear if no slowdown had been made, AC.

The pointer is placed on point "A", a planimeter reading taken, and the pointer is caused to follow the actual speed line A-B-C, then returned over the direct route C to A. The planimeter reading is taken, checked with another measurement, and then multiplied by the constant, 0.0257:-

$$67 \times 0.0257 = 1.7 \text{ minutes lost due to slowdown.}$$

It will be seen that while the actual follower on the tape traverses the area ABC, FIGURE 5, the planimeter actually traveled the path A'B'C', FIGURE 6.

3. Loss of time due to a stop. FIGURE 7, Page 17.

Difference in time between running A to C at constant speed and making a stop at B.

To obtain time lost, place pointer at point "A", FIGURE 7, read planimeter, and move pointer to B-C-A.

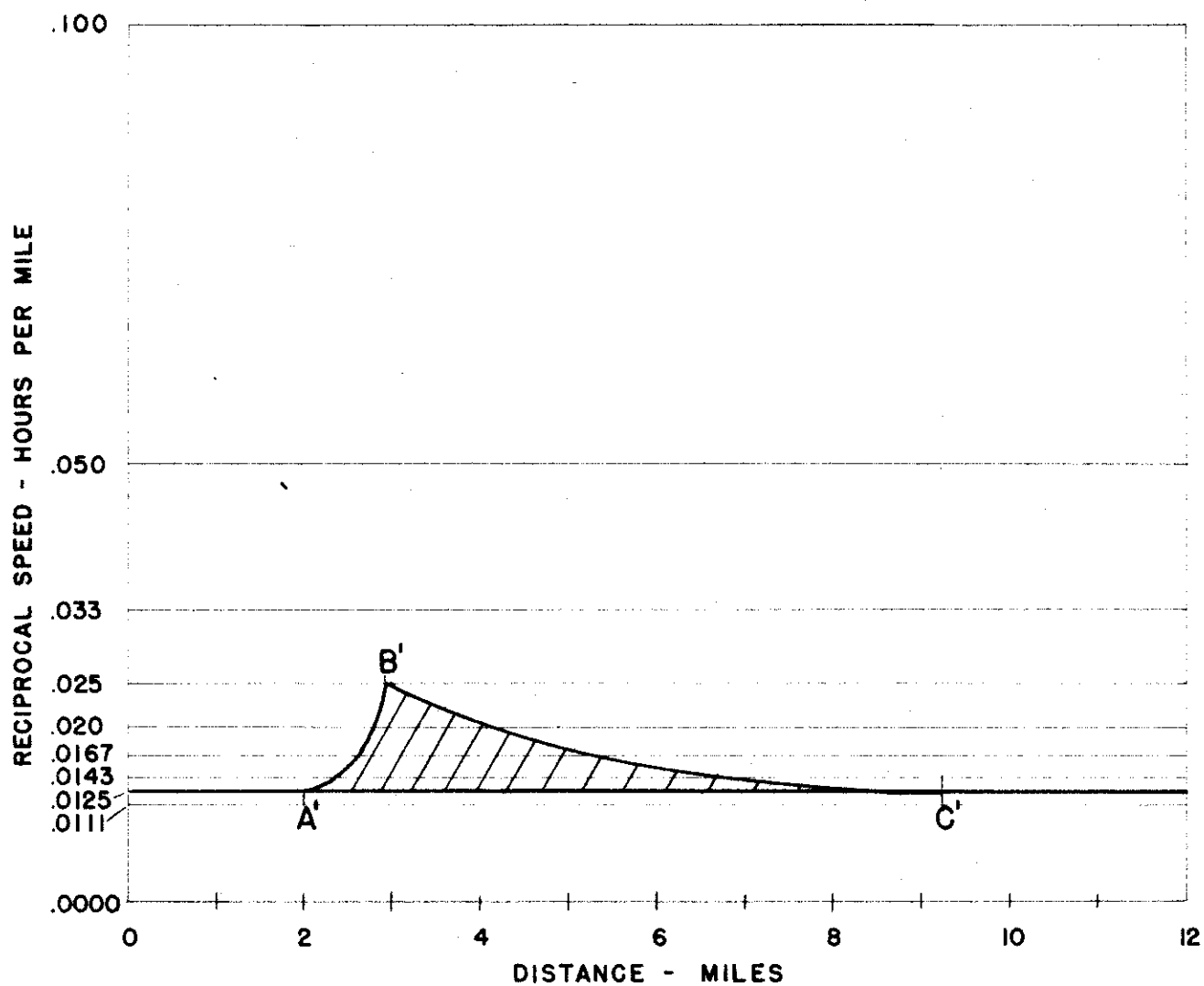


FIG. 6

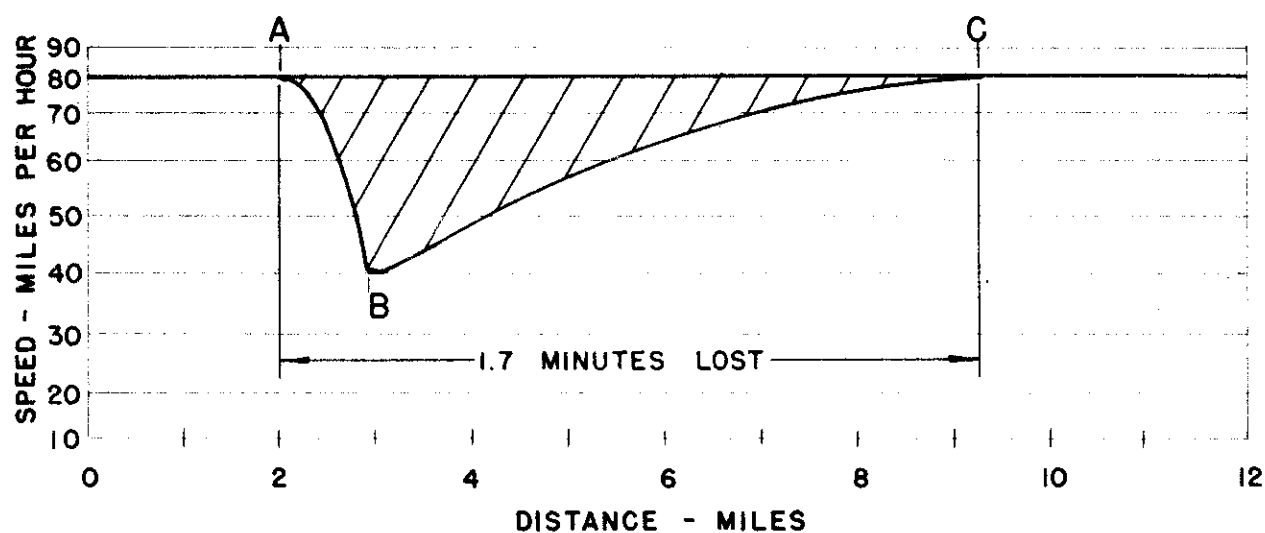


FIG. 5

EXAMPLE OF FINDING TIME LOST DUE TO A SLOWDOWN
BETWEEN POINTS "A" AND "C" ON A SPEED VS. DISTANCE GRAPH

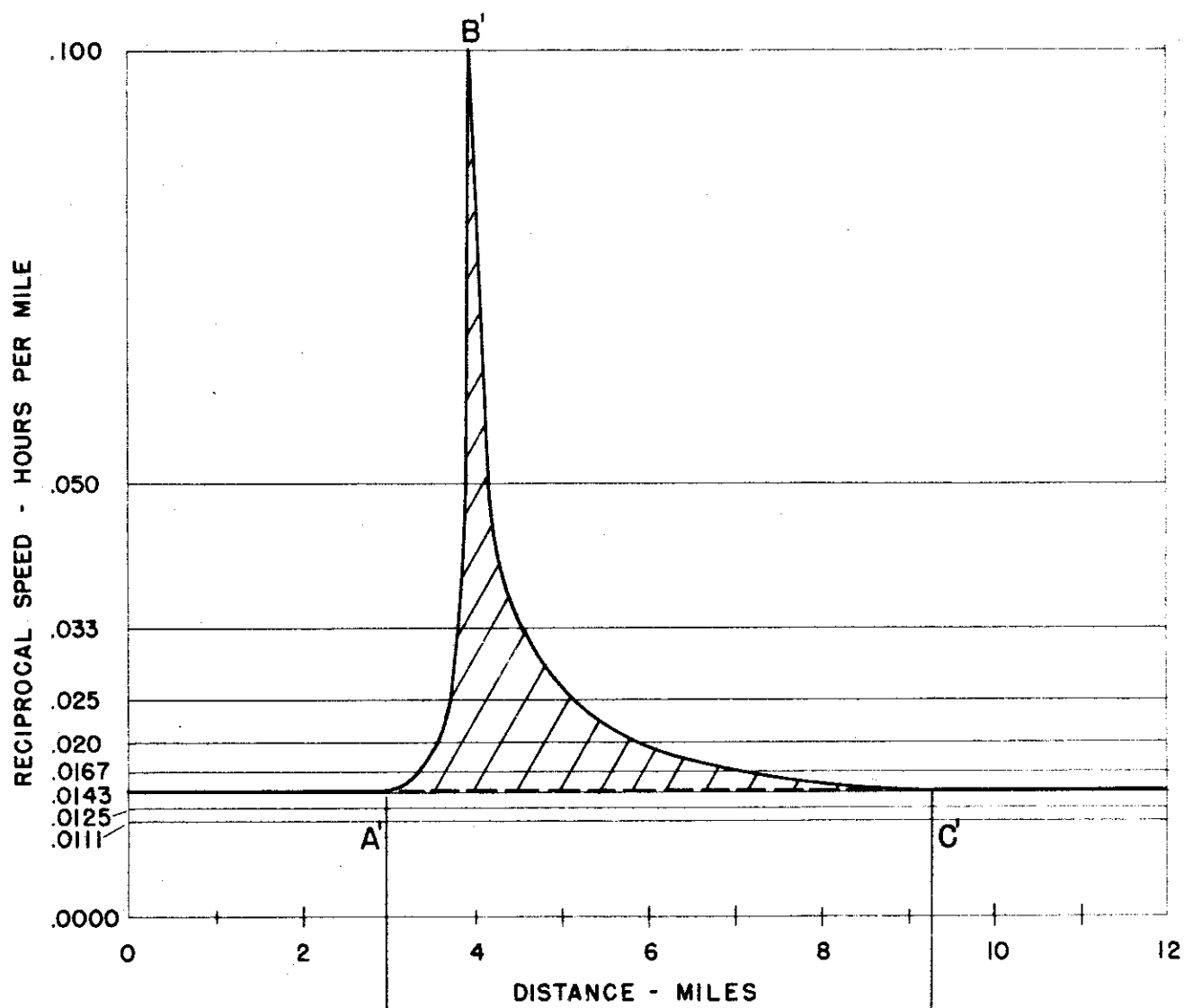


FIG. 8

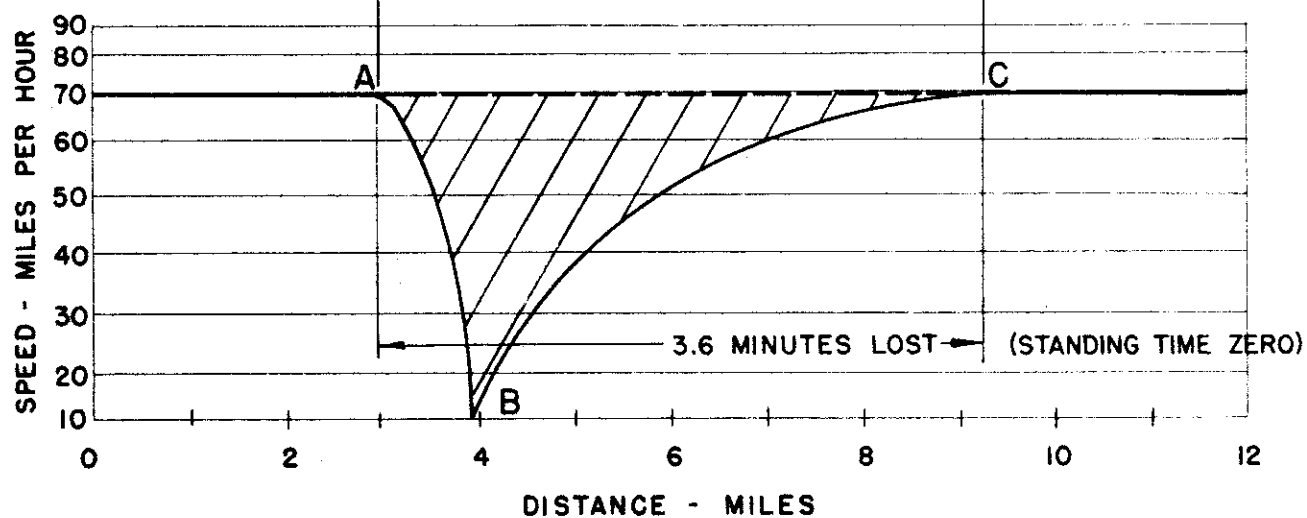


FIG. 7

EXAMPLE OF FINDING TIME LOST DUE TO A STOP
AT POINT "B" ON A SPEED VS. DISTANCE GRAPH

Read planimeter and obtain area under the reciprocal curve, which multiplied by the constant equals time lost due to the stop:-

$$120 \times 0.0257 = 3.1 \text{ minutes, from tape.}$$

It will be noted that the tapes do not record speed below 10 MPH, although the tape moves through the instrument whenever the locomotive moves. It is therefore necessary to make an allowance for the time spent below 10 MPH which is not shown on the tape. The time and distance spent in reducing speed from 10 MPH to a stop is very small and is considered negligible. Accelerating however, takes more time, and taken from actual dynamometer tests with passenger trains, an allowance of 30 seconds or 0.5 minutes is used on all starts, which allowance is added to the time found above with the calculator, thus:-

$3.1 + 0.5 = 3.6$ minutes is the actual time lost due to stopping at point "B", with standing time zero. FIGURE 8 indicates the reciprocal curve for FIGURE 7.

4. Layout of schedules based on actual locomotive records.

Such layouts are most conveniently arranged on a division basis; divisions usually ranging from 100 to 250 miles in length, and each direction considered separately. The location of all fixed points is laid out to the same scale as the speed recorder tapes, 1" equals two miles.

The maximum allowable speeds are then plotted on this tape for the whole division, and actual speed vs. distance graph speeds must not exceed these limits at any point. Actual speed recorder tapes are then selected for trains of a specific number of cars and total train weight for the division involved. A sufficient number of tapes is used to insure representative performance. A composite speed vs. distance graph is then sketched in, following the profile of the line carefully, and the finished graph is taken as representing actual good operation over the division for a certain weight train.

Timing points are selected from actual timetable practice. Although a train may not make any stops between division points, time is shown at various intermediate points, both for the use of the engineman in checking his progress over the division, and the train dispatcher in making decisions as to operating matters. These intermediate timing points are also necessary so that all other trains on the division are informed as to passing and meeting times, etc.

The composite tape is then put on the time calculator and the time between each two timing points determined. As a matter of interest and information, the time losses due to each stop and slowdown are also determined and recorded on the composite tape.

The majority of railroad timetables give time to the

nearest minute, although in congested territory the half minute is sometimes used. For the composite tapes, time is computed to the nearest tenth of a minute in order to obtain more detail, and to aid in adjusting the final time accurately to the nearest minute.

This method therefore actually represents a train plotting its own timetable, and by careful use of existing locomotive records enables the formulating of a railroad timetable which gives proper proportioning of overall division time between various timing points. Timing points either require the services of an operator, towerman or an automatic device which "OS's" trains as they pass a particular point without the services of an operator. The term "OS" is an abbreviation in standard usage meaning a "train report", and comes from the term, "Out of Station".

D. Recommendations for timetables based on results of a schedule layout using proper proportioning of time between timing points.

Time in minutes and tenths as obtained by the time calculator represents the performance of a train with a given number of cars making stops as noted on the graph. It stands for the best performance possible under good operating conditions with a similar type locomotive. Any of the conditions listed below will require more time than is shown:-

1. Bad weather
2. Head or side wind, or both
3. Bad rail condition (slippery rail)

4. Locomotive unable to duplicate performance due to being less powerful than those used in making the composite tape, or due to mechanical troubles, low steam pressure, poor firing conditions, etc.

5. Interference with other trains.

6. Unscheduled stops or slowdowns.

7. Delays due to any reason; track work, bridge work, etc.

8. More cars or train of greater weight than that used in making the composite tape.

It is therefore evident that a train schedule should be prepared with a margin of safety to compensate for any of the above listed conditions if it is to represent a timetable which can be followed by trains under all conditions, excepting accidents such as washouts and landslides which cannot be foreseen.

Likewise, a timetable generally does not specify a maximum number of cars or train weight in passenger service, but is made to handle as wide a variation in operating conditions as is practical. In some foreign countries, certain passenger trains are rigidly limited in train weight in order that fast schedules may be adhered to. However, since each added car requires more energy to pull it, it is obvious that each car added over that used on the composite tape will require more time for the train to cover the division.

Although locomotives are designed to have reserve

capacity to cope with conditions as they arise which require more power, the wisdom of shortening schedules and increasing train weights beyond practical limits may well be questioned if the "On Time" percentage is to be kept to a satisfactorily high figure. To the passengers, an "On Time" arrival is usually much preferred, even though the overall time is longer, to a shorter time, and have the train put them into their destination or transfer point late. Safety demands that maximum allowable speeds not be exceeded and therefore timetables should represent performance that it is possible to maintain in the face of all expected difficulties.

E. Solution of Special Problems.

1. Possible means of Shortening Schedules.

a. Rerouting trains.

This method is sometimes resorted to when an alternate route is available which will lessen traffic congestion. The alternate route is charted, first locating fixed points, then assigning the maximum allowable speed which would be permitted over the new route. Grades are taken into account and the speed vs. distance graph sketched in, using as a basis any locomotive speed recorder tapes available over this route. The time calculator then gives the time over the new route, and if enough time can be saved by using the new route over the original route, the trains may be rerouted to advantage. If no time can be saved by the alternate

route, its use will depend upon some factor other than time saving.

Under this same heading in a territory where congestion of trains causes progressive delays to following trains, it is often possible to install additional automatic signaling to operate trains "against the current of traffic" during certain periods of the day when opposing traffic is light. This is done under strict control to avoid any possibility of two trains entering the same track in opposing directions. It involves certain expense in additional equipment and in order to obtain a figure on total time saving the speed recorder tapes may again be referred to.

Since some time is lost due to slowing down for a crossover move from one track to another, the new alternate route must alleviate congestion and more than offset the delay due to slowing down for the crossover move.

A base tape is prepared and the location of the crossover is plotted thereon and the probable train performance on the crossover is sketched in. The time calculator will then give the time lost due to slowing down for the crossover and this figure may be used in estimating the economies of the proposed remedy which, in effect, provides the use of an additional track during peak periods of traffic.

b. Raising maximum permissible running speeds:-

The present operation is obtained from actual locomotive records and the proposed speed limits plotted on the same chart. By using the profile of the line, the new speed vs. distance graph may be sketched in, and the difference in time may be obtained by the time calculator.

c. Elimination of Stops or Slowdowns:-

The present operation at any point of speed restriction is obtained from actual locomotive records. The proposed elimination would allow speeds as sketched in, taking into account the profile of the line. The time lost is then calculated and would represent the saving if the stop or slowdown were eliminated.

2. Cost of Stops and Slowdowns.

This figure has been calculated many times and by many methods, most of which take into account many items which cannot be classed entirely "out of pocket" expense. In order to obtain readily an estimate which may be quickly arrived at, the actual speed vs. distance graphs from the locomotives are used.

In FIGURE 11, Page 26, the time lost due to slowing down from A to B is found on the time calculator, the time consumed from A to C had no slowdown been made, and the time from B to C. From the figure it will be noted that line AC denotes a train running without change of speed and the

fuel rate (pounds of coal per hour) may be readily estimated. Likewise, the curve BC represents the acceleration after slowing down from A to B. Practically no coal is used from A to B, only enough being fed to keep the fire in readiness for acceleration. For the accelerating period, the coal rate may also be readily estimated.

Therefore the loss of coal due to this slowdown is equal to time BC x lbs. coal per hour BC minus time AC x lbs. coal per hour AC. Since the amount of water evaporated by a locomotive boiler is roughly proportional to the fuel burned, this same method may be used to estimate the amount of water lost due to a stop or slowdown.

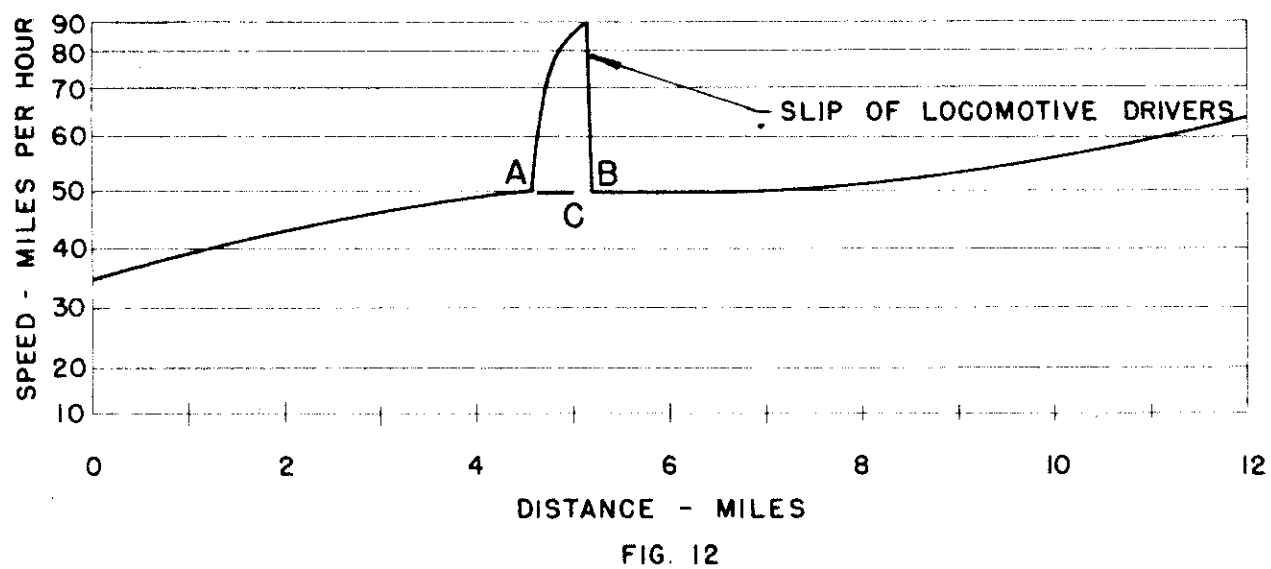
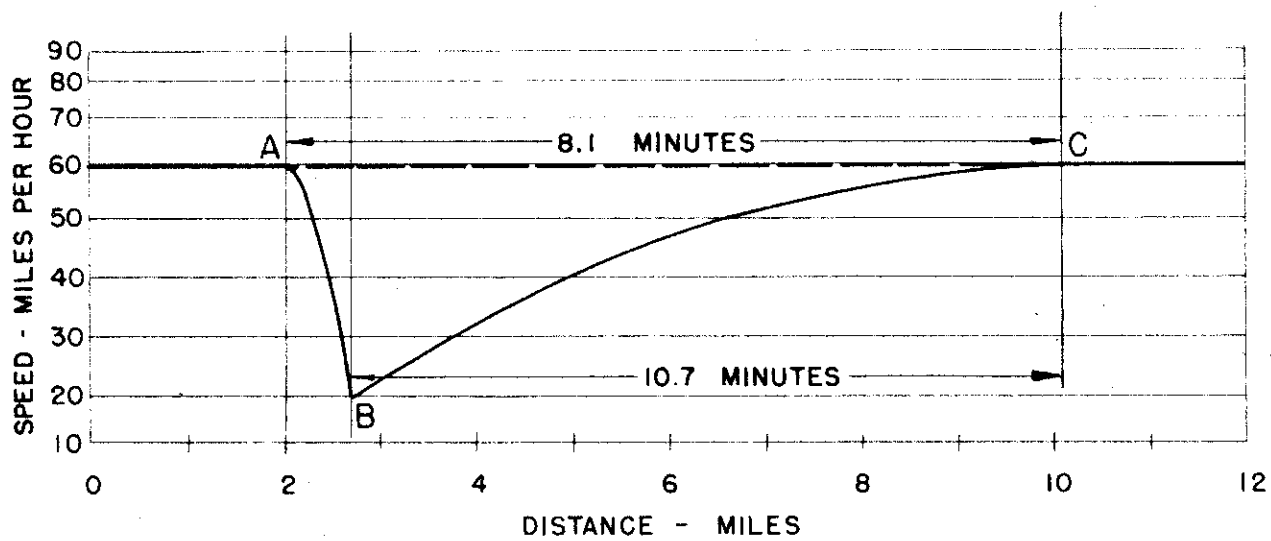
The amount of coal or water found by the above means may be converted into dollars by applying the proper cost figures which are in effect in the locality in question.

Putting into figures the example shown in FIGURE 11, Page 26, it is found that the time AC equals 8.1 minutes, and the time BC equals 10.7 minutes. Probable coal rates are as follows:-

Running, lbs. coal per hour = 7000; per minute = 117.
Accelerating, lbs. coal per hour = 11000; per minute = 183.

Therefore:

$10.7 \times 183 - 8.1 \times 117 = 1010$ lbs. coal lost due to the slowdown.



TYPICAL SPEED VS. DISTANCE GRAPHS

LOCOMOTIVE SPEED RECORDER

Since the amount of water evaporated by a passenger locomotive boiler may be approximated at 7 lbs. water per lb. coal while running, and 6 lbs. water per lb. coal while accelerating, it follows that:-

$$\text{Gal. water evap. per min.} = \frac{7000 \times 7}{60 \times 8.34} = 98 \text{ gal. per}$$

minute while running, and:-

$$\text{Gal. water evap. per min.} = \frac{11000 \times 6}{60 \times 8.34} = 132 \text{ gal. per}$$

minute, while accelerating.

Therefore in the case in FIGURE 11, Page 26;

$10.7 \times 132 - 8.1 \times 98 = 618$ gallons of water lost due to the slowdown.

If the cost of coal is \$4.00 per ton, the cost of the slowdown in fuel alone is:-

$$\frac{1010 \times 400}{2000} = \$2.02$$

3. Determination of the Amount of Slipping which occurs when a locomotive loses traction.

This figure is usually expressed in two ways; first as the maximum driving wheel speed as compared with the actual locomotive speed, and second, how many extra revolutions of the driving wheels were made during the period of slipping.

A typical slip has been reproduced from a speed vs. distance graph indicating a maximum driver speed of 90 MPH

with a locomotive speed of 50 MPH in FIGURE 12, Page 26.

Since the travel of the speed recorder tape is directly proportional to the distance traveled by the locomotive driving wheels, it does not therefore indicate locomotive distance traveled during periods when slipping occurs.

Points A and B, FIGURE 12, indicate actual locomotive speeds just before and after a slip of the driving wheels. It is assumed that the speedometer friction drive wheel does not lose contact with the driving tire during the slip.

The time calculator is run over the actual line on the tape from A to B (0.62 miles) and the time computed as 0.5 minutes. The actual locomotive speed during this slip follows the regular speed line from A to B to the point C, and is approximately 50 MPH.

The actual distance traveled by the locomotive AC equals speed (50 MPH) \times time (0.5 \div 60 hours) equals 0.416 miles, and will always be less than the distance AB. Distance CB then equals the distance traveled by the locomotive drivers in excess of that traveled by the locomotive during slipping.

If the locomotive involved had driving wheels 79" in diameter, those wheels would have turned 158 revolutions, while without slipping, they would have turned only 106 revolutions.